Isospin Equilibration processes and Cluster production

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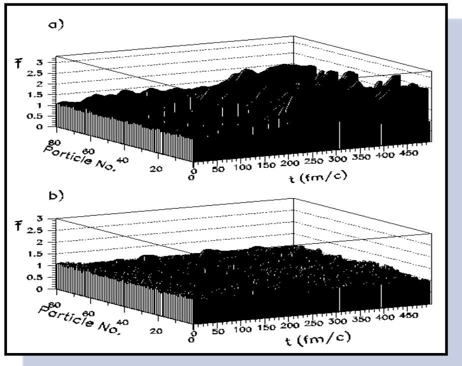
Outlines

- Symmetry interaction and microscopic many-body correlations
- Charge/Mass Equilibration processes- Deep Inelastic collision at about 5 MeV/A
- Charge/Mass Equilibration processes- Incomplete fusion processes/binary at 25 MeV/A
- Charge/Mass Equilibration processes-dipolar degree of freedom
- Summary and out-looks

CoMD-II Model and the symmetry interaction:

Main ingredient of the model:



Restoring Pauli Principle through a multi-scattering procedure (branching).

N-N scattering processes:

Restoring of the total angular momentum conservation with a suitable algorithm which further constrains the equations of motion

G.S. configuration obtained with a cooling-warming procedure producing an effective Fermi motion

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Symmetry interaction at density less than ≈1.5ρ_0:

From **deuteron** binding energy, low energy nucleon-nucleon scattering experiment

Hp 0)

T=1 i-triplet states $(N^2+Z^2+NZ)/2$ couples $\rightarrow V_1$

T=0 i-singlet states $NZ/2$ couples $\rightarrow V_0$

$$V = \left(\frac{3}{8}V_1 + \frac{1}{8}V_0\right)\rho^{a,a} + \frac{1}{8}(V_1 - V_0)(\rho^{n,n} + \rho^{p,p} - 2\rho^{n,p})$$

$V_1 > V_0 \rightarrow a_{sym} = (V1-V0)/4 > 0$

$$\boxed{\varepsilon^{\tau} = (a_{sym}/2\rho_0)F(\rho/\rho_0)\beta^2}$$

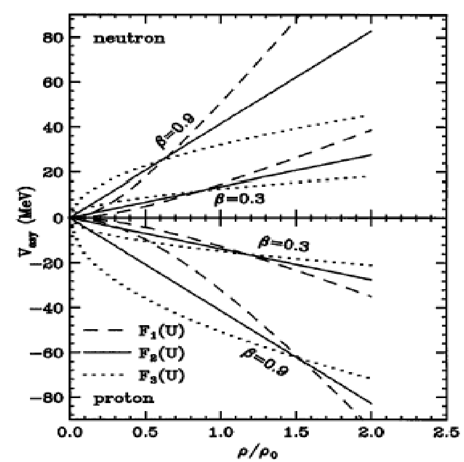
$$F_1(u) = \frac{2u^2}{1+u},$$

$$F_2(u) = u,$$

$$F_3(u) = u^{1/2},$$

$$u \equiv \rho/\rho_0$$

Bao-an Li
PRL 78 1997



Starting from the same Hp 0) but implemented in a many-body framework we get:

$$\boxed{U^{\tau} = \frac{a_{sym}}{2\rho_0}\sum_{j\neq k=1}^{A} F'(J)[\rho_{j,k}(2\delta_{\tau_j,\tau_k}-1)]} ;\quad U^{\tau}_{N.L.} = \frac{a_{sym}}{2\rho_0} F' \sum_{j\neq k=1}^{A}[\rho_{j,k}(2\delta_{\tau_j,\tau_k}-1)]$$

$$F'(J) = \frac{2S_J}{S_{gs}+S_J}\ \text{Stiff1};\quad F'(J)=1\ \text{Stiff2};\quad F'(J) = \left(\frac{S_J}{S_{g.s}}\right)^{-1/2}\ \text{Soft}$$

$$S_J = \sum_{k\neq j=1}^{A}\rho_{j,k};$$

Non Local Approximation for Form Factors (N.L.)

$$\text{For compact systems}\ U^{\tau} \approx U^{\tau}_{N.L.} = \frac{a_{sym}}{2\rho_0}F'(\rho^{N,N}+\rho^{P,P}-2\rho^{N,P})$$

$$F' = F'(S) \qquad S = \frac{4}{3A}\sum_{j\neq k=1}^{A}\rho_{j,k}$$

U^{τ} depends on the normalized Gaussian overlap integrals $\rho_{K,J}$ related to the nucleonic wave packets.

For simplicity we consider a compact system with A>>1

Leading factor

$$U^{\tau}_{N.L.} = \frac{a_{sym}}{2\rho_0}F'\beta_M;\qquad \boxed{\beta_M = N^2\tilde{\rho}^{N,N} + Z^2\tilde{\rho}^{P,P} - 2NZ\tilde{\rho}^{N,P} \neq\propto \beta^2}\qquad \left\{\begin{array}{l} U^T \\ U^c \end{array}\right.$$

$\tilde{\rho}^{I,I'} \equiv$ *Average overlap integral for couple of nucleons*

Source of correlations:

<u>Symmetry interactions</u> (major role) , the Coulomb interactions and the Pauli Principle (minor role) produce:

$$\tilde{\rho}^{N,P} > \tilde{\rho}^{N,N}, \tilde{\rho}^{P,P}\ \text{so that}\ \tilde{\rho}^{N,P} = (1+\alpha)\left(\frac{\tilde{\rho}^{N,N}+\tilde{\rho}^{P,P}}{2}\right) = (1+\alpha)\tilde{\rho}$$

Effect mainly generated by the most simple cluster the Deuton

For moderate asymmetries $\beta_M<0$

$$\alpha = \alpha\left(N, Z, \tilde{\rho}\right)$$

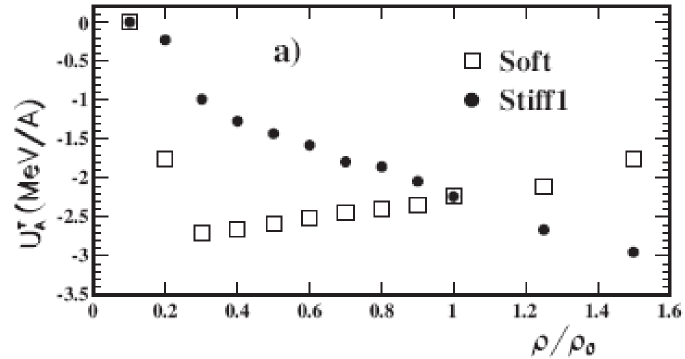
Correlation coefficient for the Neutron-Proton dynamics: <u>it is a function of N,Z and of the average overlap integral</u> (self-consistent dynamics)

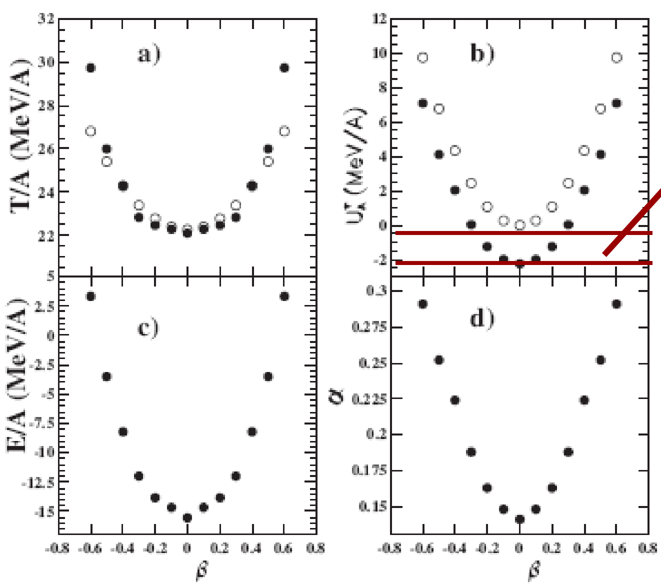
M.Papa and G.Giuliani; Eur. Phys. Journ. A 39 (2009) 117
G.Giuliani and M.Papa PRC 73 031601R (2006)

β=0 Symmetric NM

$$U^{\tau}_{N.L.} \cong \frac{a_0}{2\rho_0}\hat{\rho}A^2F'(s)[(1+\frac{1}{2}\alpha_0-\alpha')\beta^2 - \underline{\frac{1}{2}\alpha_0}]$$

$$\alpha' = \frac{1}{4}\frac{\partial^2\alpha}{\partial\beta^2}|_{\beta=0}$$

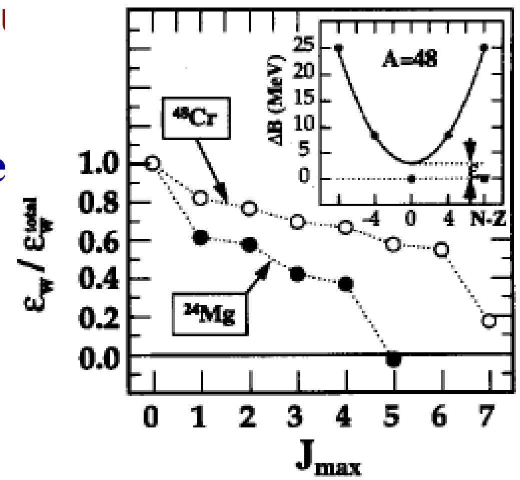




Semi-classical analogo
Wigner energy

$\alpha_0 \equiv \alpha(a_{sym,}, s, \xi)$ it decrease
with the density

$$E_W = W(A)|N-Z| + d(A)\pi_{np}\delta_{NZ}.$$



ρ=ρ$_{0.}$ Symmetric NM

ξ≡main ingredients which define
the model including the wave fucntions

F(s)=sF'(s)≡Form factors
For the iso-vectorial interaction

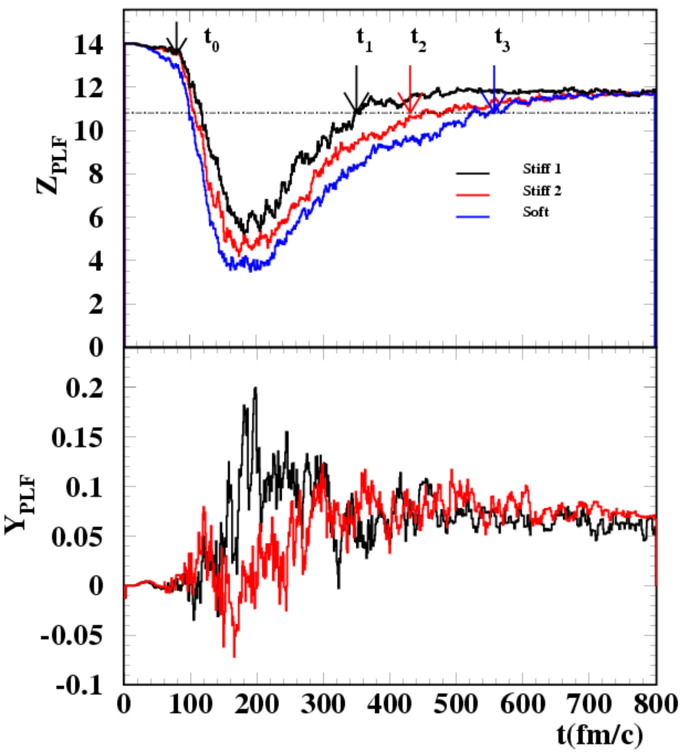
DISSIPATIVE BYNARY COLLISION AND ISOSPIN FORCES

Angular distributions measurement of the $^{28}Si+^{64}Ni$, $^{27}Al+^{58}Ni$ dissipative collisions at E_{lab}=136 and 130 MeV

M.Papa[1],G.Cremona[3],F.Amorini[2],G.Cardella[1],A.DiPietro[2],P.Figuera[2],M.Fisichella[2], M.La Cognata[2,3],M.Lattuada[23], A.Musumarra[2,3],F.Rizzo[2,3],S.Romano[2,3], G.Scalia[2],V.Scuderi[2].

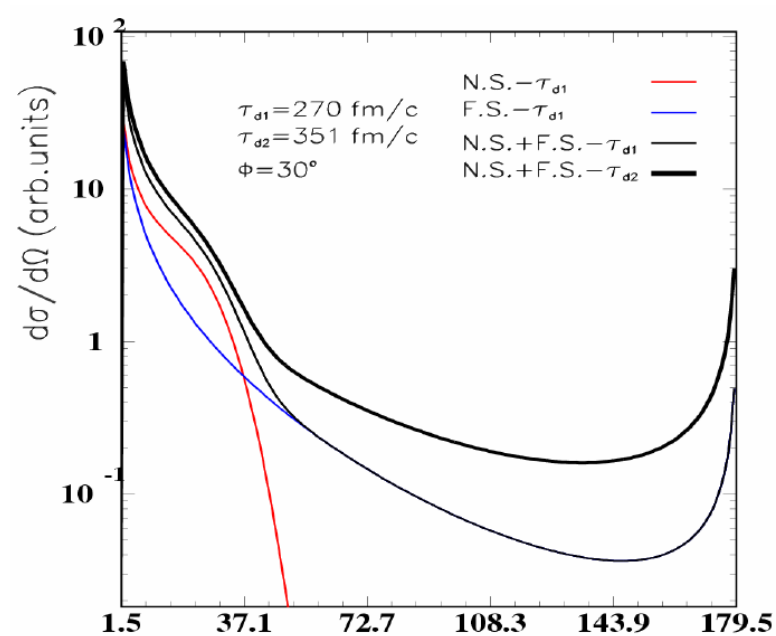
Using different options for Isospin forces we can populate similar final micro-channels (similar TKEL values, similar A,Z) but different structures of the Short lived Di-Nuclear system and different Interactions times

LNS report 2009



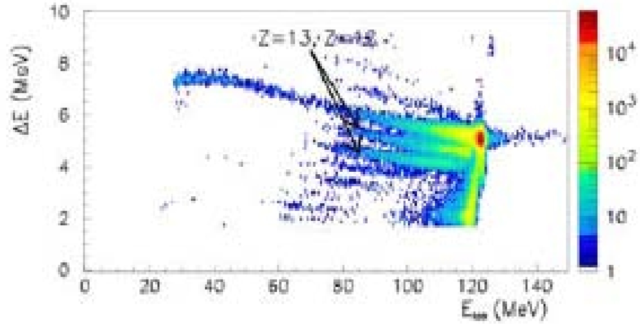
b=6 fm
TKEL=36.7
TKEL=36.1
TKEL=42.7

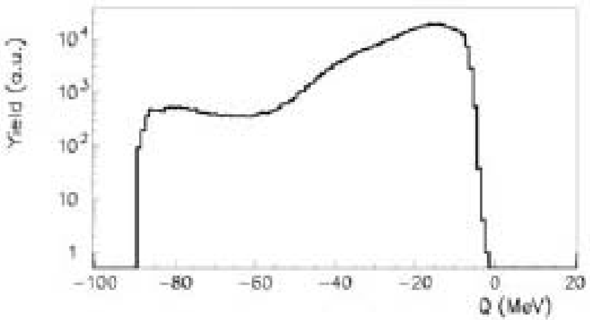
Different values of Γ/ħω



M. Papa et al; PRC 61 044614

^{28}Si+^{64}Ni compared with ^{28}Al+^{58}Ni looking for the time necessary to transfer 1 or 2 unit of charge





charge asymmetric system. According to what briefly discussed in the introductory section, this could suggest a fast transfer of 1 o 2 unit of charge from the PLF to the TLF in the case of the neutron reach target with respect to the case related to the almost symmetric ^{58}Ni targets. Clearly the results presented in this report have to be considered as preliminary ones

Figure 3 :– Angular distribution for the collisions induced by the two investigated syst and Z=12 elemental production are integrat ^{28}Si+^{64}Ni system. Z=12 and Z=11 yield are inte for the system ^{27}Al+^{58}Ni.

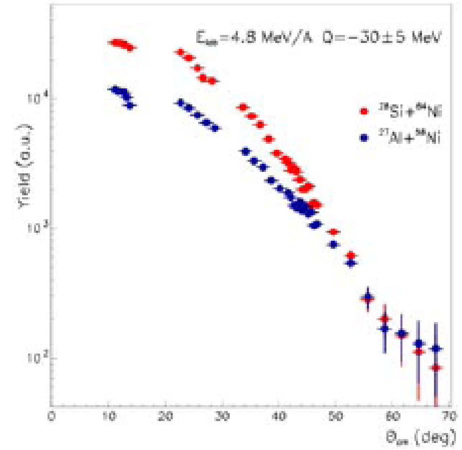
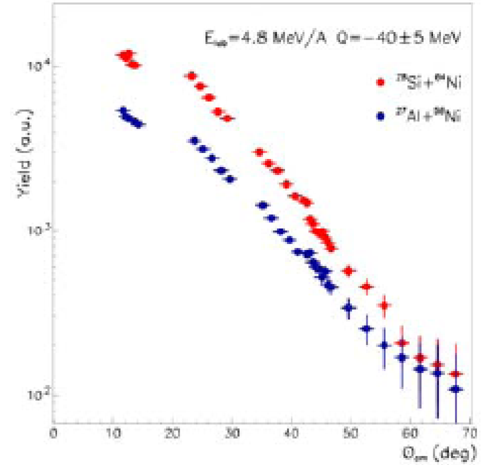


Figure 4 :– Same like Figure 3 but for a Q-valu from -45 to 35 MeV



Balance between different reaction mechanisms and Iso-vectorial forces (25 MeV/A)

Exochim-collaboration

$80\%Z_{tot}<\sum Z_i<42{,}40$ $\quad 70\%P_{tot}<\sum P_i<P_{tot}$ $\quad 0.13c<v_2$ or v_3

Selection of the PLF spectator, TLF spectator strongly suppressed low threshold on velocity

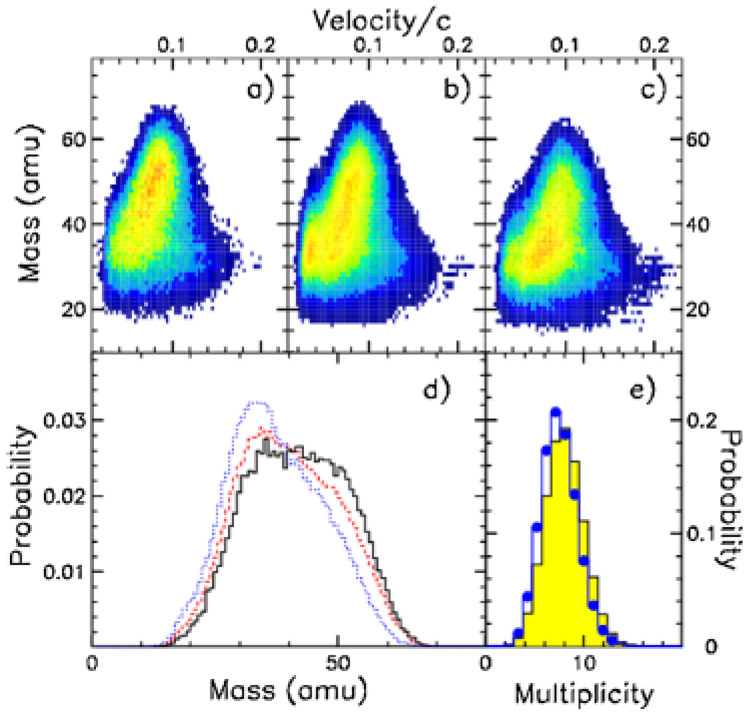


FIG. 1 (color online). Mass m_1 versus velocity v_1 of the largest fragment detected in the ^{40}Ca + ^{48}Ca (a), ^{40}Ca + ^{46}Ti (b), and ^{40}Ca + ^{40}Ca (c) reactions. (d) Projections on the mass axis for ^{48}Ca target (full line) ^{46}Ti target (dashed line), and ^{40}Ca target (dotted line). (e) Charged particle multiplicity in the reactions ^{40}Ca + ^{48}Ca (dotted histogram) and ^{40}Ca + ^{46}Ti (shaded area histogram).

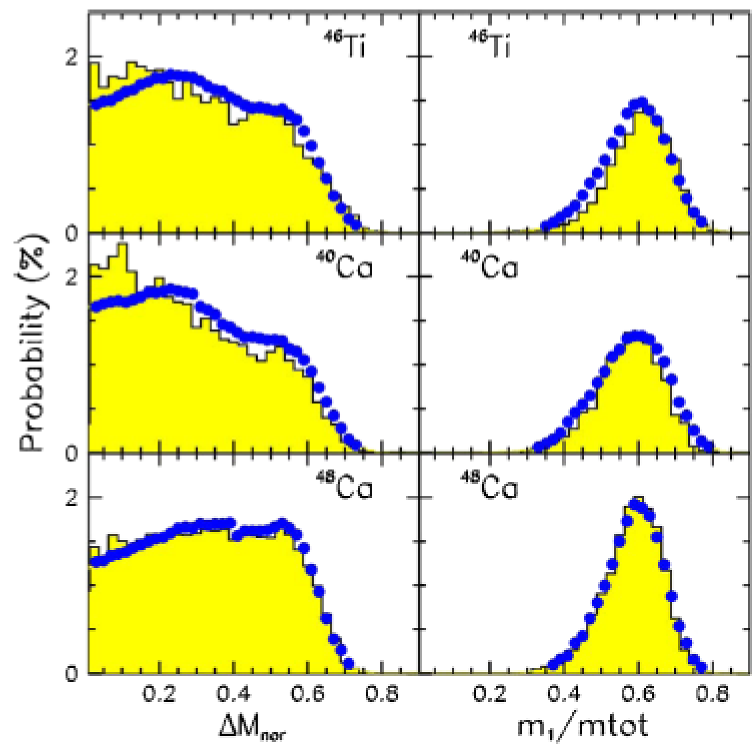
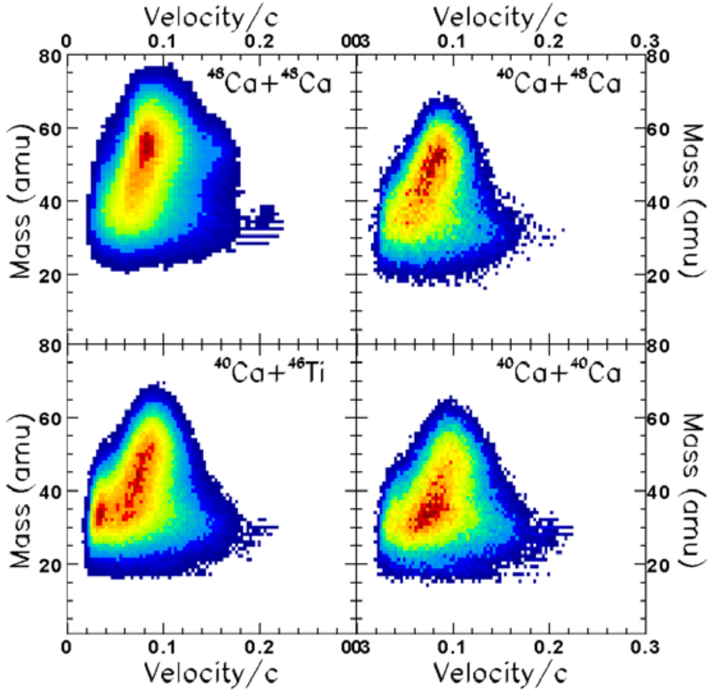
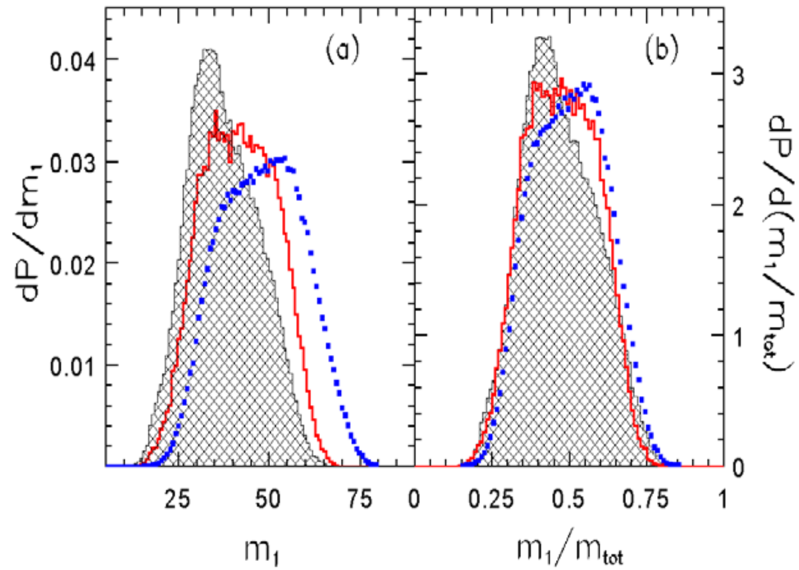


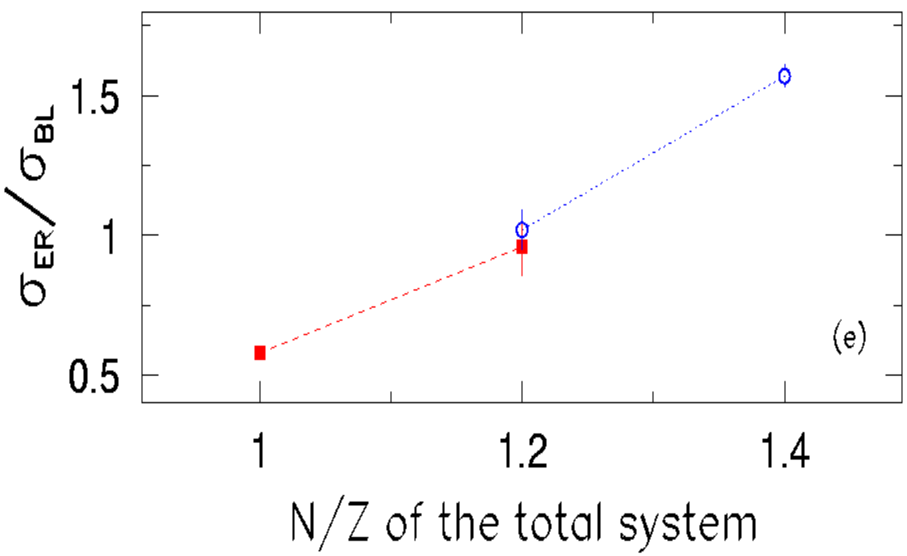
FIG. 2 (color online). Dot histograms: Probability plots of $m_1 - m_2$ and m_1 normalized to the total mass for the studied reactions. Shaded histogram: CoMD-II + GEMINI calculations. See text for details.





0 0.09 0.166 β

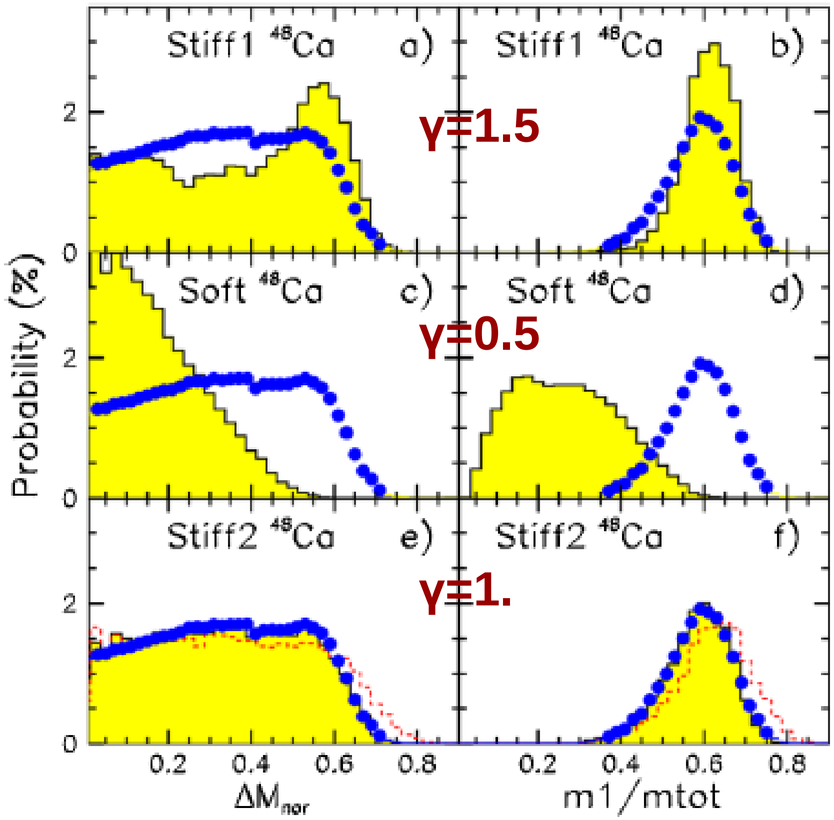
RIB
?



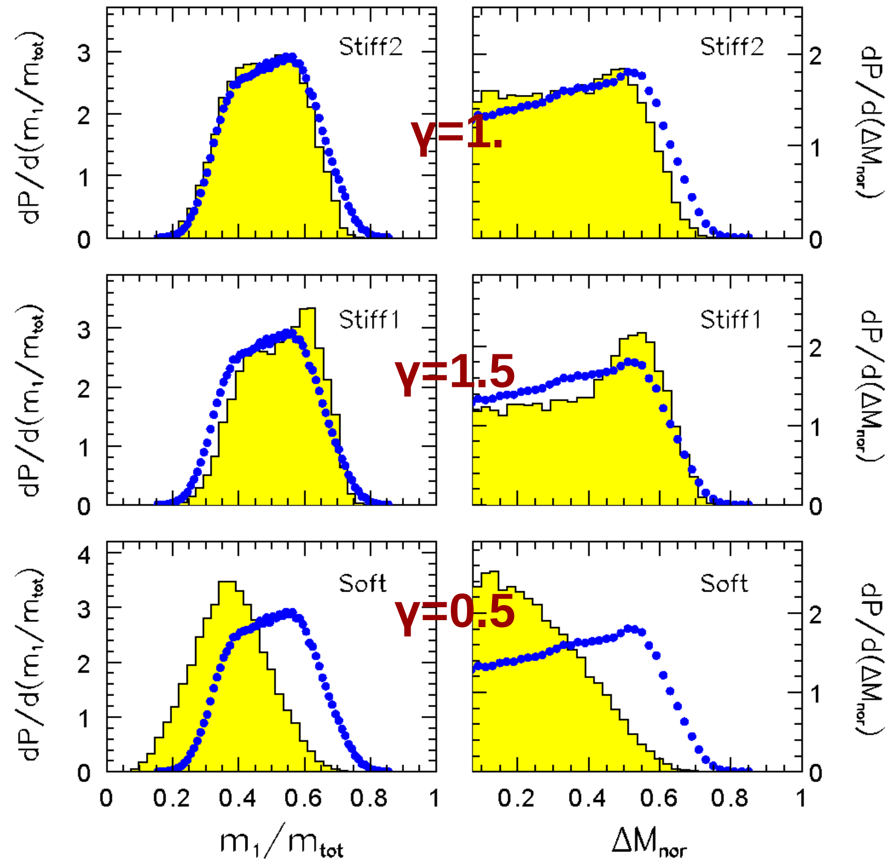
RIB
?

Comparison with ComD-II calculations

$^{40}Ca+^{48}Ca$



$^{48}Ca+^{48}Ca$



F.Amorini et al; PRL 102 112701 (2009)

Charge/Mass or "ISOSPIN" Transport In more inclusive data analysis

Determination of the yield for ^7Li and ^7Be

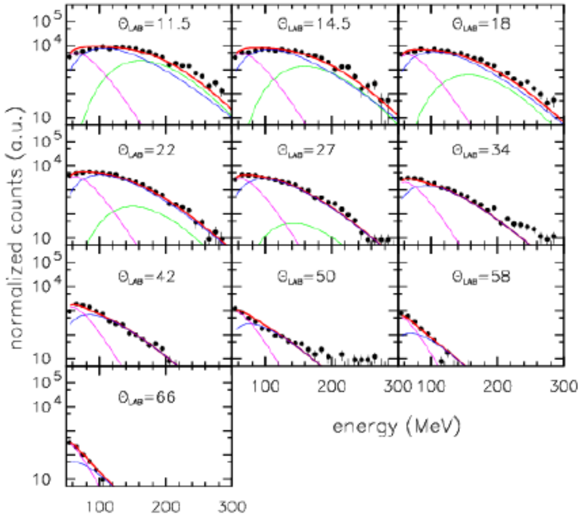


Figure 2. Kinetic energy spectra of ^7Li nuclei emitted in $^{40}Ca + ^{46}Ti$ reaction, at different values of polar angle in the laboratory frame (a similar behavior is seen for the other two reactions). Green line: QP emission. Violet line: QT emission. Blue line: MV emission. Red thick line: sum of the three contributions.

$$\frac{d^2N}{dEd\Omega} = \sum_{i=1}^{3} N_i \sqrt{E - E_c} \times \exp\left[-\frac{E - E_c + E_{S,i} - 2\sqrt{(E - E_c)E_{S,i}}\cos\theta}{T_i}\right] (1)$$

3 moving source fit with Maxwelian curve

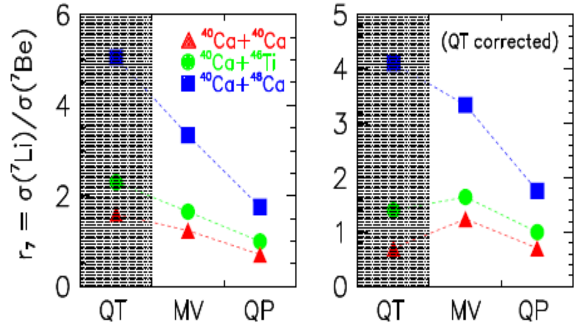
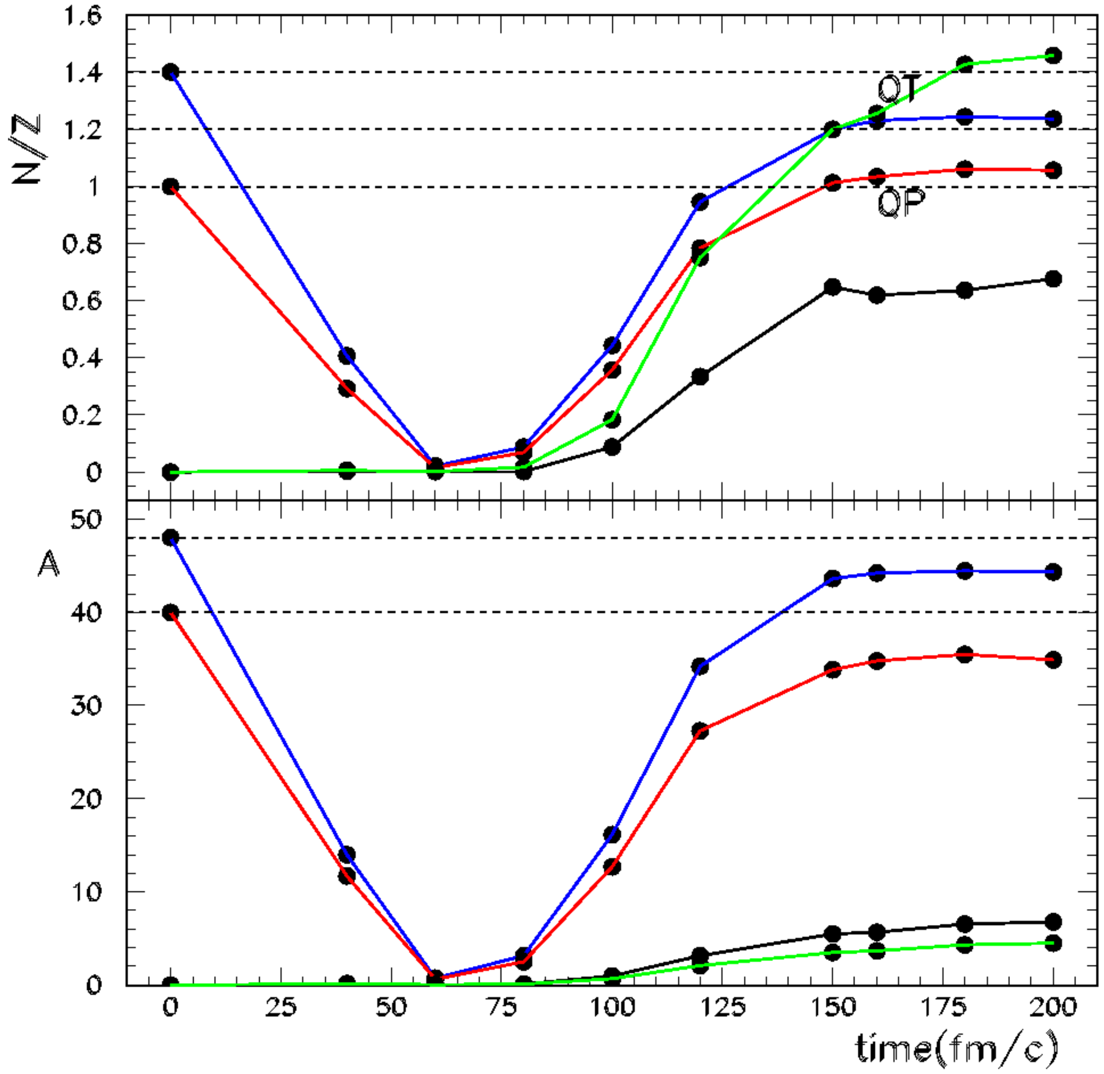


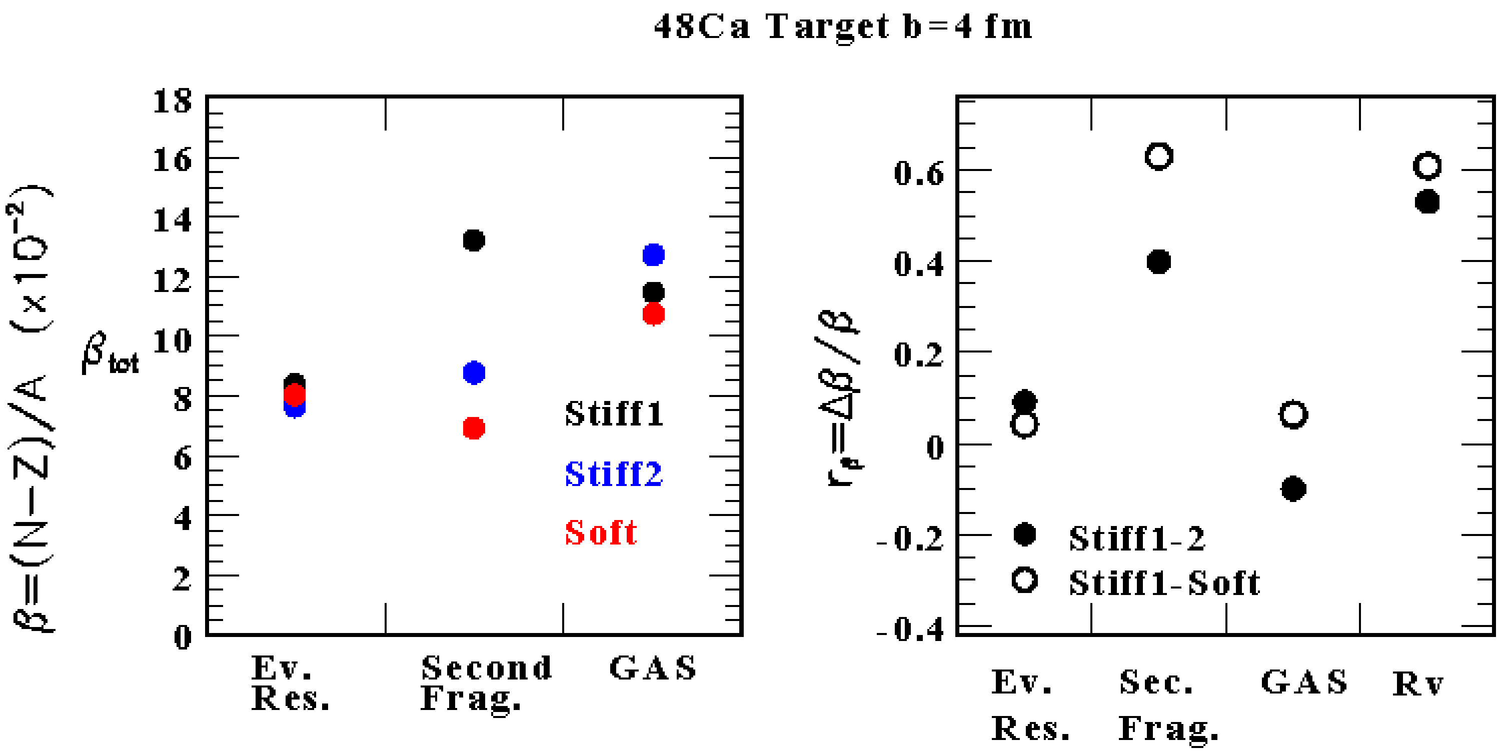
Figure 4. (left panel) Isobaric yield ratios $^7Li/^7Be$ for the three different reactions, as obtained from the moving source analysis. QP, QT and MV emissions are shown. (right panel) The same, but in this case r_7 values for QT emission have been corrected by the systematic error. Due to the identification thresholds, the shadow area have to be regarded with some caution.

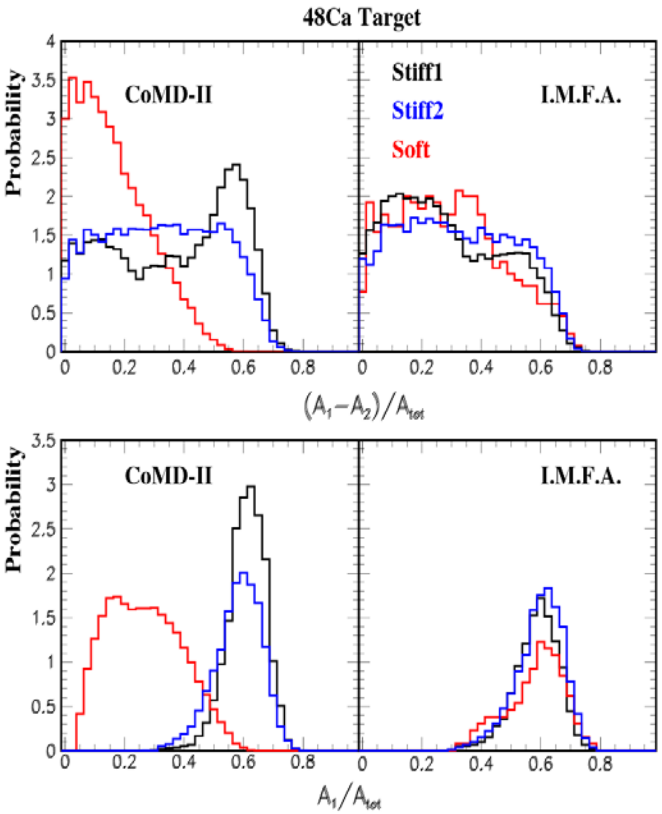
The analysis results seems to indicate memory effect of the initial charge/mass asymmetries. For the symmetric source and neutron enrichment at mid-rapidity

Not enough time for ISOSPIN DIFFUSION processes



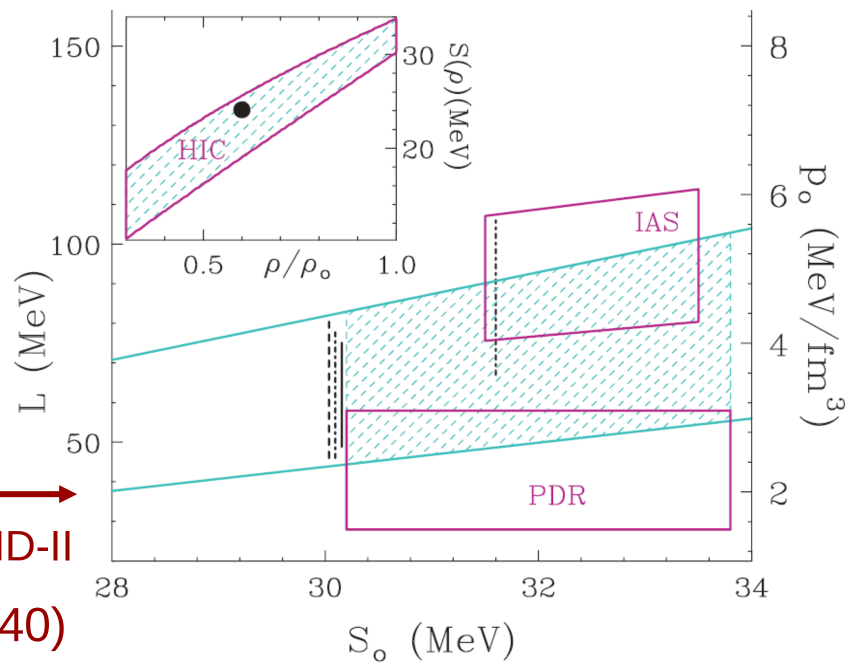
Incomplete fusion processes and charge/mass repartition





Constraints on E_{sym}

$L = 3\rho_0 dE_{sym}/d\rho|_{\rho 0}$



(39,103)

I.M.F.A

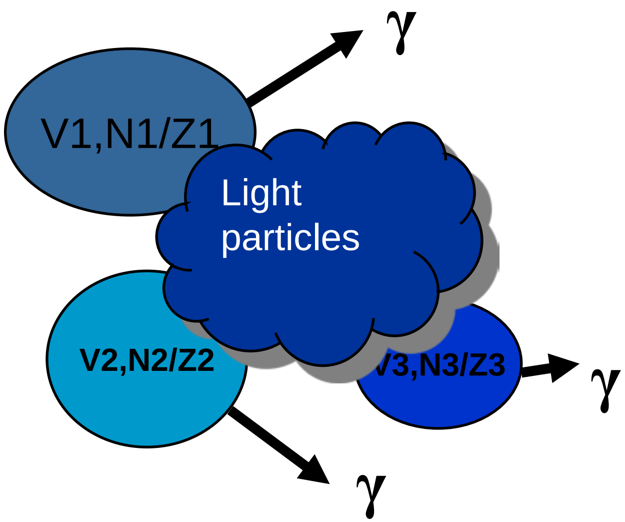
$P_0 = \rho_0 L/3$

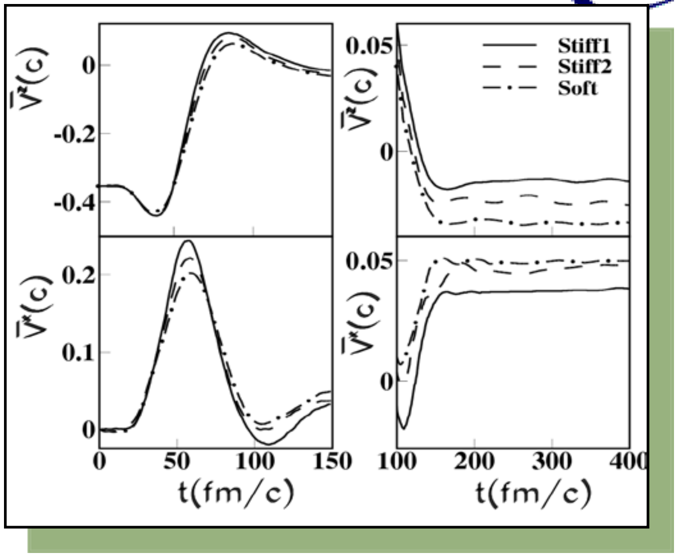
CoMD-II

(26,40)
From N.M.
simulations

Isospin equilibration and Dipolar degree of freedom

THINKING TO THE SYSTEM IN A GLOBAL WAY





As shown from CoMD-II calculations, a useful observable to globally study the Isospin equilibration processes of the system also in multi-fragmentation processes, is <u>the time derivative of the average total dipole</u> $\overline{\vec{V}}(t)$ [4].

$$\vec{V}(t) = \sum_{i=1}^{Z_{tot}} \vec{v}_i.$$

$$\overline{\vec{V}} = \sum_{Z,A} \frac{Z}{A} \overline{m_{Z,A}\langle\vec{P}\rangle_{Z,A}}\, C^{Z,A}_{\langle\vec{P}\rangle}$$

$$C^{Z,A}_{\langle\vec{P}\rangle} = \frac{\overline{m_{Z,A}\langle\vec{P}\rangle_{Z,A}}}{\overline{\langle\vec{P}\rangle}_{Z,A}\,\overline{m}_{Z,A}}$$

- <u>**-it is invariant with respect to statistical processes;**</u>
- <u>**-it depends only on velocities and multiplicities of charged particles;**</u>
- <u>**-it has a vector character allowing to generalize the equilibration process along the beam and the impact parameter directions;**</u>

$\overline{\vec{V}} = 0$ **General condition for Isospin equilibration**

[4] M. Papa and G. Giuliani, arxiv:0801.4227v1 [nucl-th].
[5] M. Papa and G. Giuliani, submitted to Jorn of. Physics

<V(t)> simple properties and the “Isospin ”

$$\left\langle \vec{V}(t) \right\rangle = \left\langle \sum_{Z;A} m^{i}{}_{Z,A} Z \, \vec{v}^{cm}{}_{Z,A} \right\rangle_i \longrightarrow \langle \vec{V} \rangle = \sum_{Z,A} \frac{Z}{A} \langle m_{Z,A} \rangle \langle \vec{P}_{Z,A} \rangle C^{Z,A}_{\vec{P}}$$

Correlation between multiplicity and velocity $\longrightarrow$ $C^{Z,A}_{\vec{P}} = \dfrac{\langle m_{Z,A} \vec{P}_{Z,A} \rangle}{\langle \vec{P}_{Z,A} \rangle \langle m_{Z,A} \rangle}$

The quantity can be reconstructed from the asymptotic values of all (global variable) but only charged particles and related velocities. It is invariant with respect to statistical decay processes

The asymptotic value is then established by the early dynamical stage case of a strictly binary processes (a.p.f U_c)

The simple case of a strictly binary processes

$$\langle \vec{V} \rangle \approx \langle \vec{V}_M \rangle = \frac{1}{2} \langle \mu_{PT} \rangle \langle \beta_T - \beta_P \rangle \langle \vec{v}_{PT} \rangle \qquad (1)$$

$$\mu_{PT} = \frac{A_P A_T}{A_P + A_T} \quad \text{reduced mass}$$

$$\beta_{P,T} = \frac{N_{P,T} - Z_{P,T}}{A_T} \quad \text{neutron excesses;}$$

$$\vec{v}_{PT} = \vec{v}_P - \vec{v}_T \quad \text{relative velocity}$$

Global Neutron-Proton relative motion (bound and un-bound Nucleons) is implicitly taken in to account trough the total momentum conservation

<V> Equilibrium value

•In binary processes if $\beta_T = \beta_P$ ↔ <V(t)>=0

$$\langle \vec{V} \rangle \approx \langle \vec{V}_M \rangle = \frac{1}{2} \langle \mu_{PT} \rangle \langle \beta_T - \beta_P \rangle \langle \vec{v}_{PT} \rangle \qquad (1)$$

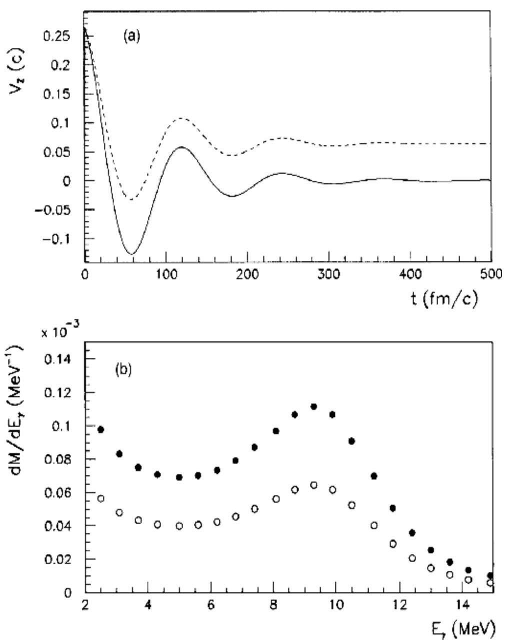
•Pre-equilibrium γ-ray emission, ΔT=1

•Common operative definition of equilibrium value for an isospin sensitive observable X
A and B similar system with different Charge/Mass ratio

$$X_{A+B} = \frac{X_{A+A} + X_{B+B}}{2}$$

X≡ <V> ; $\langle V \rangle_{A+A} = \langle V \rangle_{B+B} = 0$
Then $\langle V \rangle_{A+B} = 0$

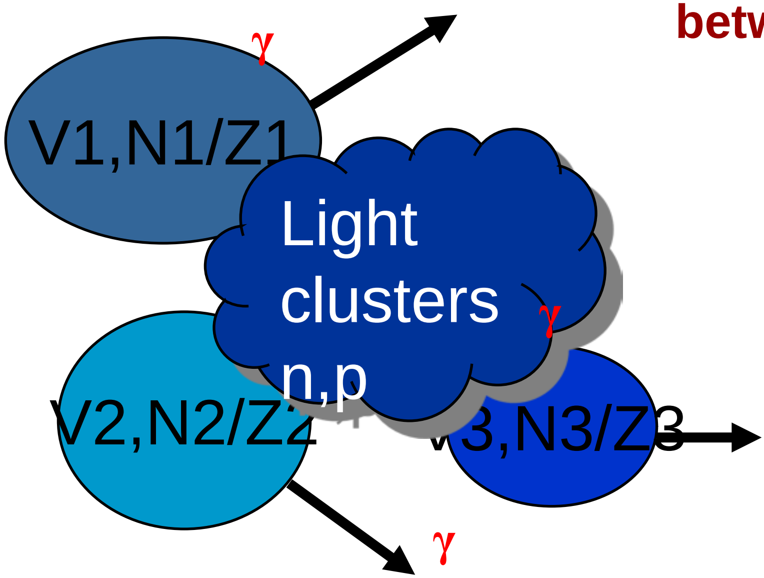
For a fixed damping with the maximum γ – ray emission is obtained for **<V(t)>** =0



All these arguments allow us to extend the same concept of equilibrium to more complicated (behind the binary picture) processes as the one which are tipically produced at the Fermi energies

Equilibration <V> =0 in less simple processes and relations with other Isospin related phenomena

$$\langle\vec{V}\rangle = \langle\frac{A_G(1-\beta_G^2)}{4}\vec{v}_r^{\,PN}\rangle+\langle\frac{\mu_{GL}(\beta_L-\beta_G)}{2}\vec{v}_{cm,LG}\rangle + \langle\vec{V}_{r,L}\rangle$$



<V>=0 requires a delicate balance between different contribution.

We can consider disassembly of an hot source trough n and p emission and trough a statistical production of fragment $\langle\vec{V}_{r,L}\rangle = 0$ If $\langle\vec{v}_r^{\,PN}\rangle = 0$ "Isospin" Equil. means β_G= 1 and/or $\langle\vec{v}_{cm,LG}\rangle = 0$

If $\langle\vec{v}_{cm,LG}\rangle \neq 0$ and $\beta_G \neq \beta_L$ due to Isospin. Distillation

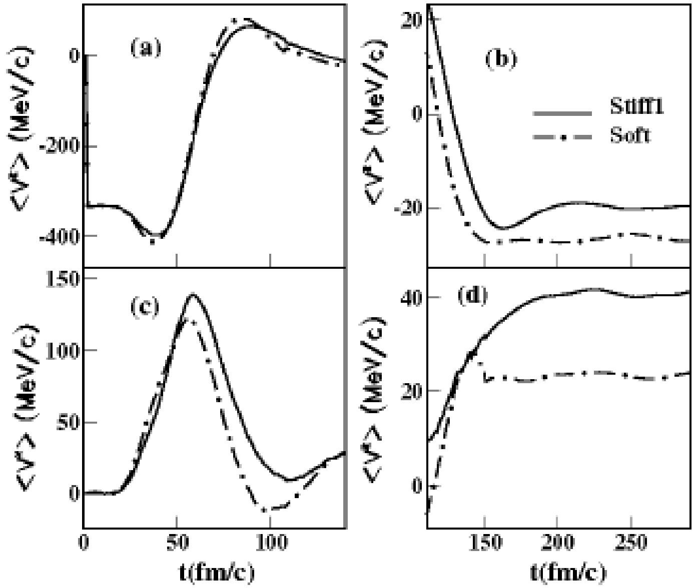
Then the spontaneus equilibration of the dipolar degree of freedom implies $\langle\vec{v}_r^{\,PN}\rangle \neq 0$

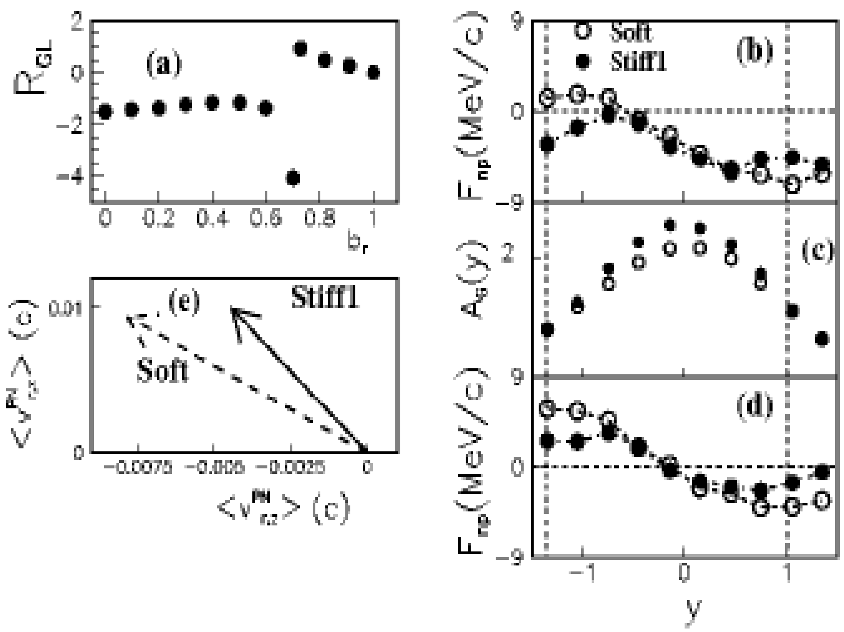
Production of Differential neutron-proton Flow

Dipolar degree of freedom and Iso-Vectorial Forces

$^{40}Cl+^{28}Si$ at 40 MeV/nucleon CoMD-II prediction

$$R_{GL} = \frac{\langle V_G^z \rangle}{\langle V_L^z \rangle}$$





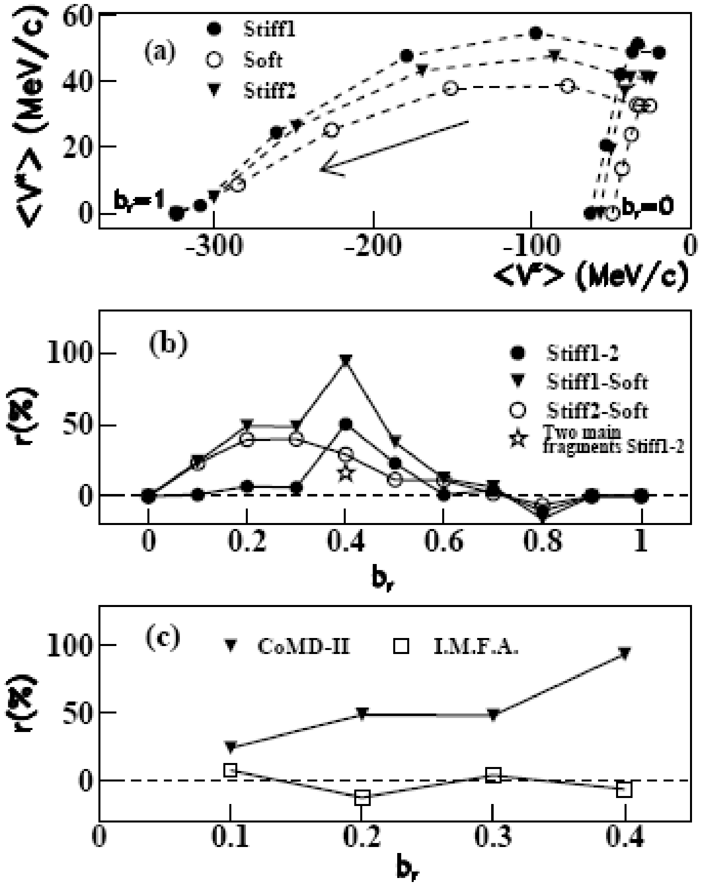


Fig. 3. (a) $\langle V^x \rangle$ is plotted as a function of the corresponding $\langle V^z \rangle$ value for different reduced impact parameter b_r values ($b_{max} \simeq 7.5$ fm and $\Delta b_r = 0.1$) and different options (different symbols). The arrow indicates the direction of increasing impact parameters. -(b) relative changes r for the ratio R (see the text) evaluated for different couples of options as a function of b_r. -(c) Values of r evaluated for the Stiff1-Stiff2 options as a function of b_r are plotted in the case of full CoMD-II calculations and in the case of I.M.F.A. approximation (see the text). The lines which join the points are meant only to guide the eye through the shown trend.

Symmetry interaction

$$U^\tau = \frac{a_{sym}}{2\rho_0} \sum_{j \neq k=1}^{A} F'(J)[\rho_{j,k}(2\delta_{\tau_j,\tau_k} - 1)] \; ; \quad U^\tau_{N.L.} = \frac{a_{sym}}{2\rho_0} F' \sum_{j \neq k=1}^{A} [\rho_{j,k}(2\delta_{\tau_j,\tau_k} - 1)]$$

$$F'(J) = \frac{2S_J}{S_{gs}+S_J} \text{ Stiff1}; \quad F'(J) = 1 \text{ Stiff2}; \quad F'(J) = \left(\frac{S_J}{S_{g.s}}\right)^{-1/2} \text{ Soft}$$

$$S_J = \sum_{k \neq j=1}^{A} \rho_{j,k};$$

Non Local Approximation for Form Factors (N.L.)

For compact systems $U^\tau \approx U^\tau_{N.L.} = \frac{a_{sym}}{2\rho_0} F'(\rho^{N,N} + \rho^{P,P} - 2\rho^{N,P})$

$$F' = F'(S) \qquad S = \frac{4}{3A} \sum_{j \neq k=1}^{A} \rho_{j,k}$$

Looking at the numbers: The signal related to the “gas phase-Light clusters” plays at these energiesa prominent role for the Equilibration processes

As an example, for b = 3 fm and for the Stiff2 option, the "liquid" asymptotic values are $\langle V^x_L \rangle = -111.8$ MeV/c and $\langle V^z_L \rangle = 150.9$ MeV/c while the total contributions are $\langle V^x \rangle = 44.9$MeV/$c$ and $\langle V^z \rangle = -25.15$ MeV/. Therefore,

M.Papa and G.Giuliani; Eur. Phys. Journ. A 39 (2009) 117
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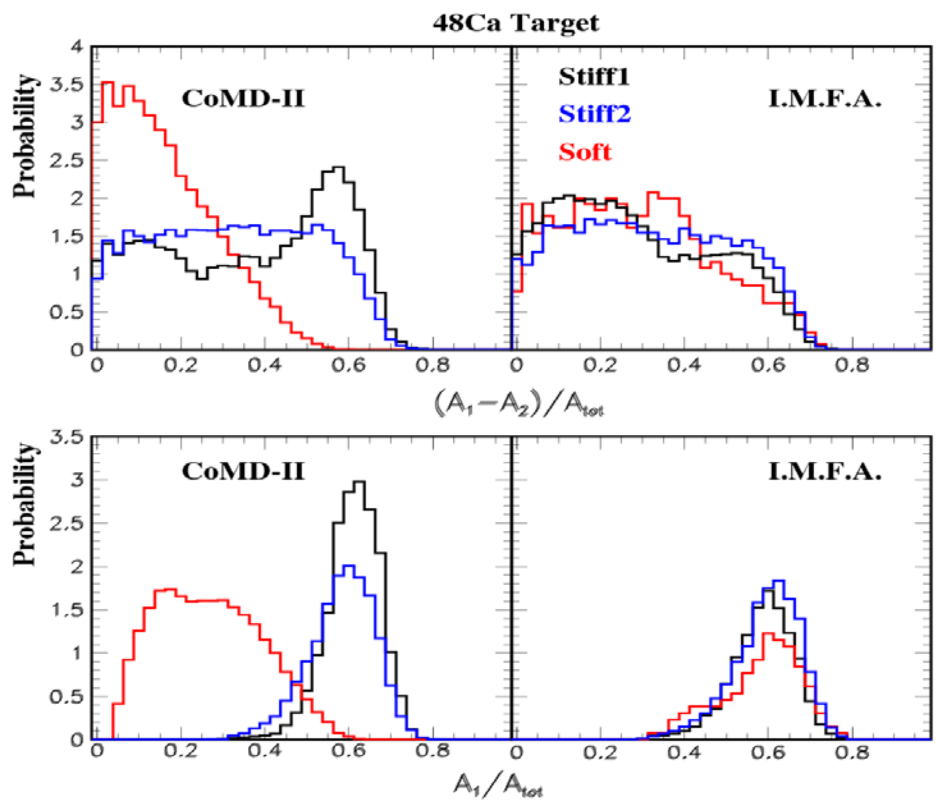
Summary

- Some examples have been shortly discussed concerning the cluster production, reaction mechanisms, interaction times in typical processes induced through heavy ion collisions at low energy.

- Many-body correlations induced by Iso-vectorial forces ensure a large sensitivity of simple observables from the main parameters describing Isospin forces also in the dynamics of heavy ion collisions at low energy.

- The study of this correlations seems to us a necessary step forward for a better understanding of the dynamics related to the Isospin degree of freedom.


48Ca Target
Probability
CoMD-II
Stiff1
Stiff2
Soft
I.M.F.A.
(A1−A2)/Atot
CoMD-II
I.M.F.A.
A1/Atot
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.4
0.6
0.8